A Final Report On

MILLIMETER-WAVE RADIOMETRIC MEASUREMENTS OF ATMOSPHERIC WATER VAPOR AT THE DEPARTMENT OF ENERGY'S NORTH SLOPE OF ALASKA CLOUD AND RADIATION TEST SITE

Submitted to

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Introduction

During March 1999, the NASA/Goddard Space Flight Center and the NOAA/ Environmental Technology Laboratory conducted a joint experiment at the ARM NSA/AAO site in Barrow, Alaska. The major focus of the experiment was to determine if millimeter wavelength radiometers can measure significant changes in atmospheric water vapor during very cold and dry winter arctic conditions. Theoretical studies indicate that the relative accuracy of Precipitable Water Vapor (PWV) measurements derived from microwave radiometer data diminishes as conditions become very dry, i.e. PWV < 5mm. The reduced accuracy results from using the weak absorption line at 22 GHz. Studies show that millimeter wavelength radiometers operating around the 183 GHz water vapor line provide a greatly enhanced sensitivity, perhaps some 30 times as great. The Millimeter Wave Radiometric Arctic Winter Experiment was conducted using a large inventory of microwave and millimeter radiometers, operating from 20 to 350 GHz. The instruments were operated in the harsh arctic environment for a three week period in March 1999. In addition to the NASA and ETL radiometers, the infrastructure facilities provided at NSA/AAO (in particular, ARM communication and housing facilities, MWRs, cloud lidars and radars, AERI, as well as once-a-day radiosondes) were of substantial benefit. During the experiment a wide range of atmospheric conditions were experienced and an excellent data set was obtained to meet the experiment's objectives.

Accomplishments

Since the experiment, much progress has been made in the processing and analyzing of the data. We have also made significant progress in evaluating the utility of millimeter wave radiometry for measuring low PWV. Following is a summary highlighting our most significant accomplishments.

- NASA and NOAA/ETL deployed a suite of radiometers covering the spectral range from 20 to 350 GHz. High quality radiometric measurements were made over a twenty three day period between March 7 through March 30, 1999. Edited portions of these data have been delivered to ARM by NASA and ETL.

- A probability distribution of PWV constructed using National Weather Service radiosondes shows that there are a high percentage of cases in which PWV is less than 3 mm; i.e., those cases in which 183 GHz radiometry is promising.

- Weighting function analysis shows the greatly enhanced sensitivity of the 183 region to water vapor at low concentrations (PWV < 3 mm); at higher concentrations (PWV > 5 mm), the sensitivity of the ARM MWR is adequate. This analysis confirms an earlier one showing that the 183 GHz channels and the existing MWR channels could provide complete coverage during all of the PWV conditions encountered at Barrow.

- Comparisons of contemporary absorption models show that substantial differences exist between the models at some of the transparency channels that were operated during the experiment. The differences in various absorption models represent a substantial fraction of the error in retrieved PWV values. Determining an adequate model will have substantial benefit to remote sensing by millimeter wavelength radiometry.

- Application of calibration methods, including the "tipping calibration" method and both hot and ambient calibration reference targets, indicates that data from two completely independent radiometric systems (NASA/GSFC and ETL) were in basic agreement. The average difference between the ETL and NASA/GSFC brightness temperatures (CSR – MIR) are 2.02, -2.25, 0.18, and 0.45 K for the 183 +/-1, 183 +/- 3, 183 +/- 7, and 340 GHz channels, respectively.

- Several very cold, dry, and clear days have been analyzed and these data show substantial fluctuations in the millimeter wave brightness temperatures (some 25 to 30 K) while corresponding variations in the ARM MWR were less than 0.5 K.

- Original radiosonde data and those corrected using Vaisala's algorithm (by Barry Lesht) showed differences of 1 to 2 mm. At low vapor concentrations, these differences are 20%, and would be difficult to discern by the MWR alone. Even larger differences were observed in comparison with National Weather Service soundings at Barrow.

- Comparisons of forward modeled brightness temperature calculations based on radiosondes profiles and radiometer measurements show differences at times of 10 K. These differences could be due to uncertainty in radiosonde data, absorption models, radiometer calibration or, most likely a combination of all three.

- Images produced by the window channels of the scanning radiometers during cloudy conditions show the potential of millimeter radiometry for studies of arctic clouds.

- The physical retrieval algorithm developed by Jones and Racette was augmented to allow the water vapor distribution to vary during the convergence process. This change reduces the residual brightness temperature upon convergence.

- Single-channel and multi-channel retrievals have been performed using a combination of microwave and millimeter wave data. Differences in the retrieved values are consistent with differences observed in the forward model brightness temperature comparisons. Differences are attributed to errors in the absorption model, background temperature field, and radiometric calibration errors.

- PWV comparisons made of measurements derived from millimeter-wave measurement and those from the two MWR systems, showed large discrepancies.

Upon closer examination, the discrepancies were found to be due to calibration errors in the MWR. A new calibration algorithm for the MWR was developed and applied to the data. After recalibrating the MWR, better agreement was achieved between the MWR and millimeter-wave measurements. The recorrected MWR data have been delivered to ARM by ETL.

- A study was performed comparing retrieved PWV using the rotating shadow-band spectrometer and PWV based upon microwave measurements. Good agreement was achieved using these two completely different measurement techniques. The results of the study are presented in the peer-reviewed publication by Kiedron et al.

- A time series of atmospheric profiles at 15-minute increments were generated for the period of the experiment. The time series profiles are based upon the 5-mm radiometer data that were used to derive low-tropospheric temperature files and the MWR retrieved PWV that were used to scale the radiosonde humidity profile. A subset of these retrievals has been delivered to the ARM archive.

- Sets of zenith brightness temperatures collected during the intensive observation period along with data documentation were delivered to the ARM archive.

- **The following publications and presentations resulted directly from the support received for this study.**

1. P. Racette, A. Gasiewski, E.R. Westwater, Y. Han, E. Kim, K. Widener, and B. Zak "Millimeter-wave Radiometric Arctic Winter Measurements," ARM Science Team Meeting, San Antonio TX, March 1999.

2. P. Racette, E. Kim, E.R. Westwater, Y. Han, A. J. Gasiewski, "Retrieval Of Low Amounts Of Precipitable Water Vapor Using Millimeter-Wave Radiometric Measurements," 22nd General Assembly of the International Union of Geodesy and Geophysics, IUGG99, Birmingham England, July 1999.

3. P. Racette, E.R. Westwater, and Y. Han, "Millimeter wave Radiometric Measurements made during the 1999 Arctic Winter," ARM-IRF meeting, October 1999, Albany, New York.

4. E.R. Westwater, Y. Han, and P. Racette, "Water vapor and temperature weighting Functions at millimeter wave for very dry conditions," ARM-IRF meeting, October 1999, Albany, New York.

5. E.R. Westwater, Y.Han, P. Racette, and A. Gasiewski, "Millimeter-wave Radiometric Arctic Winter Water Vapor Experiment," 26th International Union of Radio Science (URSI) General Assembly, Toronto Canada, August 1999.

6. Y. Han, E.R. Westwater, P. Racette, W. Manning, A. Gasiewski, M. Klien, "Radiometric Observations of Water Vapor during the 1999 Arctic Winter Experiment," ARM Science Team Meeting, San Antonio TX, March 2000.

7. E.R. Westwater, Y. Han, P. Racette, W. Manning, A. Gasiewski, M. Klein, "A Comparison Of Clear Sky Emission Models With Data Taken During The 1999 Millimeter-Wave Radiometric Arctic Winter Water Vapor Experiment," ARM Science Team Meeting, San Antonio TX, March 2000.

8. P. Racette, E.R. Westwater, Y.Han, W. Manning, A.Gasiewski, D. Jones, "Millimeter-wave Radiometric Measurements of Low Amounts of Precipitable Water Vapor," ARM Science Team Meeting, San Antonio TX, March 2000.

9. P. Racette, E.R. Westwater, Y.Han, W. Manning, A.Gasiewski, D. Jones, "Millimeter-wave Measurements of Low Amounts of Precipitable Water Vapor," Proc. International Geophysics And Remote Sensing Symposium '00, July 2000, Honolulu, Hawaii.

10. Westwater, E. R., Racette, P. E., Han, Y., Leuski, V., and D. Cimini, "The Arctic Winter Millimeter-Wave Radiometric Experiment: Summary, Conclusions, and Recommendations," ARM Science Team Meeting, Atlanta, Georgia, March 19 - 23, 2001.

11. P. Kiedron, J. Michalsky, B. Schmid, D. Slater, J. Berndt, L. Harrison, P. Racette, E. Westwater, and Y. Han, "A robust retrieval of water vapor column in dry Arctic conditions using the rotating shadowband spectroradiometer," Journal of Geophysical Research, in press.

Work continues on the analysis of the data collected during the experiment in preparation of another peer-reviewed publication based upon the data set.

Conclusions and Recommendations

The theoretical basis of using 183 GHz radiometers to improve MWR retrievals of PWV at low amounts is sound. A variety of simulations and theoretical considerations all suggest that about 4% accuracy can be obtained during clear conditions, for PWV less than about 20 mm. However, retrieval of PWV using millimeter-wave radiometric measurements is complicated by uncertainties in the absorption models, atmospheric temperature profiles, and calibration of the millimeter-wave measurements.

Forward-modeled brightness temperatures of dry atmospheres differ when different absorption models are used. Our calculations show that substantial (~10 - 15 K) differences exist between the various models at some of the millimeter-wave frequencies. Our estimated radiometric calibration accuracy allowed us to resolve some, but not all, of the problems. For the MWR channels, the Liebe 1993 model agreed with better than 0.1 K bias and a standard deviation of better than 0.2 K rms. However, for the millimeter wave channels, the Liebe 93 model significantly over predicted Tb by 5.9, 8.8, and 13.3 K. The uncertainties in RAOB measurements of water vapor, coupled with MIR and CSR calibration uncertainties of perhaps 3 K, did not allow us to make a clear choice between the Liebe 87 and the Rosenkranz 98 absorption models. This is not a fundamental limitation of the 183 GHz region, but reflects the fact that a more comprehensive database of brightness temperatures and high quality radiosonde measurements is needed.

Comparisons of NWS radiosondes launched at Barrow with those of ARM launched at the CART site showed agreement in PWV usually in the range of about 0.05 cm, although simultaneous radiosondes were not available. Because of the long database of NWS radiosondes, and because currently, only one radiosondes per day is launched at the NSA/AAO CART site, a more definitive radiosonde comparison is recommended. Because of the excellent data that is produced by the ARM MWR, perhaps the simultaneous operation of MWRs at the CART site and at the NWS facility, could aid in such a study.

For window frequencies and channels beyond perhaps ± 5 GHz from the 183 GHz absorption line center radiometer calibration can benefit by using the tipcal method. Unfortunately, for the MIR radiometer during our experiment, two-sided tipcals were not possible, and hence some residual uncertainties (~3 K) existed. Again, this is not a fundamental limitation, but is one that can be overcome by equipment design. Any future experiments using millimeter radiometry should focus on achieving better calibration.

Excellent temperature profiles can be derived from a scanning 5-mm radiometer if a radiosonde temperature profile is used for an initial guess. The availability of such data can improve millimeter wave measurement-based retrievals in two ways: the derived profiles can be used to determine real-time mean radiating temperatures for tipcals. Second, the derived profiles can be scaled by MWR PWV measurements to provide a high quality first guess for the183 GHz based retrievals.

Based upon the findings of the first Millimeter-wave Arctic Winter Water Vapor study, we recommend a second more comprehensive experiment be conducted that incorporates the above recommendations. A reasonable time frame for such an experiment would be a 3 – 4 week period during the winter of 2002-2003.